Title: Skin wettedness is an important contributor to thermal behavior during exercise and recovery

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Abstract:

We tested the hypothesis that mean skin wettedness contributes to thermal behavior to a greater extent than core and mean skin temperatures. In a 27.0±1.0ºC environment, 16 young participants (8 females) cycled for 30 min at 281±51 $W \cdot m^{-2}$, followed by 120 min seated recovery. Mean skin and core temperatures and mean skin wettedness were recorded continuously. Participants maintained a thermally comfortable neck temperature throughout the protocol using a custom made device. Neck device temperature provided an index of thermal behavior. Linear regression was performed using individual minute data with mean skin wettedness, core and mean skin temperatures as independent variables and neck device temperature as the dependent variable. Standarized beta coefficients were used to determine relative contributions to thermal behavior. Mean skin temperature differed from pre-exercise (32.6±0.5ºC) 10 min into exercise (32.3±0.6ºC, $P<0.01$). Core temperature increased from 37.1±0.3ºC pre-exercise to 37.7±0.4ºC by end-exercise ($P<0.01$), and remained elevated through 30 min recovery (37.2±0.3ºC, $P<0.01$). Mean skin wettedness increased from pre-exercise (0.14±0.03 a.u.) at 20 min into exercise (0.43±0.09 a.u., $P<0.01$) and remained elevated through 80 min recovery (0.18±0.06 a.u., $P \leq 0.05$). Neck device temperature decreased from 26.4±1.6ºC pre-exercise to 18.5±8.7ºC 10 min into exercise ($P=0.03$) and remained depressed through 20 min recovery (14.4±11.2ºC, $P<0.01$). Mean skin wettedness (52±24%) provided a greater contribution to thermal behavior compared to core (22±22%, $P=0.06$) and mean skin (26±16%, $P=0.04$) temperatures. Skin wettedness is an important contributing factor to thermal behavior during exercise and recovery.

Keywords: Thermoafferent feedback, thermoregulation, thermoregulatory behavior, exercise, recovery

Introduction

Skin wettedness is a measure of the proportion of the skin that is wet at any given time (16). In most situations, skin wettedness occurrs secondary to sweating and sweat buildup in the microclimate (16). Gagge *et al*. (15) were the first to identify that increases in skin wettedness contribute directly to increases in perceptions of thermal discomfort, independent of changes in body temperature. This was later confirmed by Fukazawa and Havenith (12), who demonstrated a linear relationship between skin wettedness and thermal discomfort. Despite this, the afferent stimulus for thermal discomfort is commonly reported as the change in mean body temperature, a factor derived from the weighted average of core and mean skin temperatures (2, 11, 18). This approach disregards the contribution of skin wettedness to thermal discomfort. Further to this, studies aiming to model thermal comfort and physical activity neglect the contribution of skin wettedness to thermal comfort, likley due to a lack of empirical evidence (22, 34).

Thermal discomfort is the precursor to thermoregulatory behavior (30). In addition to autonomic thermoeffectors (e.g. sweating, skin blood flow), thermal behavior aids in restoring and maintaining thermal comfort during rest and exercise (10, 29). We previously showed that mean skin and core temperatures contribute 30 and 70%, respectively, to thermal behavior during exercise and recovery (35). However, were unable to identifty the contribution of skin wettedness in this study. Nevertheless, skin wettedness has been proposed to be a significant factor in driving thermal behavior during exercise (10, 14, 19). Skin wettedness cools the skin via evaporative mechanisms and the conscious awareness of wettedness may outweigh the perceptual signals originating from changes in mean skin and/or core temperature (15). The importance of skin wettedness to thermal behavior, relative to core and mean skin temperatures, however, remains unknown. Therefore, the purpose of this study was to determine the relative contributions of skin wettedness, core temperature, and mean skin temperature to thermal behavior during exercise and recovery. We hypothesized that mean skin wettedness contributes to thermal behavior to a greater extent than core and mean skin temperatures during exercise and recovery.

Methods

Participants

Sixteen young, healthy adults (8 females) completed this study. The participant characteristics are listed in Table 1. All participants were physically active, normotensive, non-smokers, not taking medications, cognitively normal, and free from any known cardiovascular, metabolic, neurologic or psychological diseases. Female participants were not pregnant, which was confirmed via a urine pregnancy test, and self-reported to be normally menstruating. To control for menstrual cycle hormones, all trials for females were performed during the first 10 days following self-identified menstruation or during the placebo phase of their oral contraceptives (n=4), a period in which estrogen and progesterone are at their lowest levels. Each subject was fully informed of the experimental procedures and possible risks before giving informed written consent. The study was approved by the Institutional Review Board at the University at Buffalo, and performed in accordance with the standards set by the latest revision of the declaration of Helsinki. Participants visited the laboratory on two occasions. Visit one was a screening and familiarization visit and visit two was the experimental trial.

Instrumentation and measurements

Height and weight was measured with a stadiometer and scale (Sartorius Corp. Bohemia, NY, USA), and body surface area was calculated accordingly (1). Skinfold thickness was measured in duplicate at the chest, axilla, triceps, subscapula, abdomen, suprailliac, and thigh (Harpenden, Baty International, UK), and percent body fat was estimated from body density (31), which was calculated from the sum of skinfolds measurements for males (20) and females (21). Aerobic fitness was determined using a ramped protocol (detailed below). Cognitive ability was measured using the Montreal Cognitive Assessment (25). Urine specific gravity was measured in duplicate using a refractometer (Atago USA, Inc., Bellevue, WA, USA) to test that participants were euhydrated prior to performing the trial.

A 3-lead ECG (DA100C, Biopac Systems, Inc. Goleta, CA, USA) was used for monitoring heart rate. Blood pressure was measured using manual sphygmomonometry every 10 minutes throughout the protocol. Skin blood flow was measured continually on the dorsal aspect of the left forearm via laser Doppler flowmetry (Periflux System 5010, Perimed, Stockholm, Sweden).

Metabolic data were obtained via a mouth piece with a one-way non-rebreathing valve (Hans Rudolph, Inc. Shawnee, KS, USA) at the end of 10 min pre-exercise timepoint, at 15 and 30 minutes during exercise and every 30 minutes during post-exercise. Minute ventilation was calculated from expired airflow measured via a heated pneumotachometer (Hans Rudolph, Inc. Shawnee, KS, USA), which was continuously integrated over 1 min and corrected to standard temperature, pressure, dry (STPD). The fractions of expired oxygen and carbon dioxide (VacuMed, Ventura, CA, USA) were continuously measured from a 3 L mixing chamber. Oxygen uptake and carbon dioxide production were calculated using the Haldane Transformation. The rate of metabolic heat production was calculated from oxygen uptake and the respiratory exchange ratio (RER) using a standard equation (7).

Approximately 60 min prior to any experimental testing, participants swallowed a telemetry pill (HQ Inc., Palmetto, FL, USA) for the measurement of core temperature. Participants were restricted from ingesting any fluids or food immediately after ingesting the pill and until the end of the protocol. In the event that a subject had contraindications to swallowing a core temp pill, a rectal thermistor (Mon-a-therm; Mallinckrodt Medical, Inc., St Louis, MO, USA) was inserted by the subject, 10 cm beyond the anal sphincter (n=1). Mean skin temperature was measured as the equally weighted average of ten thermochron iButtons (Maxim Integrated Products Inc., San Jose, CA, USA) attached to the left side of the body on the lower shin, posterior calf, posterior thigh, anterior thigh, abdomen, chest, scapula, hand, triceps and forehead (33).

Local sweat rate was measured by tightly securing a capsule that covered $3.9cm^2$ of the skin on the axilla and posterior shoulder on the left side of the body. Dry nitrogen was perfused through the capsule at a rate of 0.5L/min, allowing for measurement of the water vapour exiting the gas capsules to be continusoulsy measured by capitance hygrometry (HMT130, Vaisala, Woburn, WA, USA). Local sweat rate was calculated by multiplying the humidity output by by the flow rate of the dry nitrogen and dividing that value by the surface area of the capsule. The local sweat rates are reported as an average of both areas.

Relative humidity of the skin was measured using 8 hydrochron iButtons (Maxim Integrated Products Inc., San Jose, CA, USA) placed directly adjacent (within 1-2 cm) to the thermocron iButtons used to measure skin temperature at the forehead, chest, upper arm, forearm, sub-scapula, abdomen, anterior thigh and calf. At each location, the iButton was raised ~6 mm off the skin using a custom made capsule that allowed airflow to pass through. The distance of 6 mm, as opposed to the standard 2 mm, was chosen because it ensured that the humidity sensor of the iButton would not become artificially supersaturated due to a droplet of sweat entering the hygrosensor. 6 mm was deemed acceptable based on pilot testing performed in our laboratory that identified no differences between 2 mm and 6 mm in the measured relative humidity. Relative humidity from the iButtons placed on each site were used to determine the water vapour pressure of the skin using standard calculations as previously reported by Filingeri et al. (8). Finally, local skin wettedness was calculated according to the methods of Gagge (16). Whole body mean skin wettedness was calculated as the equally weighted average of all 8 local skin wettedness sites.

Neck skin temperature was measured using a single thermocouple taped to the dorsal aspect of the neck. Thermal behavior was objectively measured using techniques modified from those of Cabanac et al. (4, 5), which are currently in use in our laboratory (29, 35). In this model, participants were instructed to control the temperature of the dorsal aspect of the neck so that it is thermally comfortable throughout the experiment. The neck was chosen because it is the only skin area known to be equally and highly sensitive to both cooling and heating (24). Thus, neck skin and neck device temperatures provide objective and continuous measures of thermal behavior (4, 5). Neck temperature was controlled using a dual tubing system that was in constant contact with the subject's neck (20 cm x 10 cm). This tubing system contains two unique series of tubing. One series was continually perfused with a thermoneutral (34°C) water. The other series was perfused by a cold fluid (-20°C), and the flow of this fluid was directly controlled by the subject via a two-way ball valve. This permitted a range of neck skin temperatures (~35 to ~20°C) that were rapidly achieved (within ~15 s) when the neck was perceived to be thermally uncomfortable. The temperature of the effluent fluid immediately following contact with the neck was measured using a single thermocouple embedded in the tubing of the neck device. This neck device temperature provided a precise indication of when, and the extent by which, participants behaviorally thermoregulated (35).

Perceptual measures for the whole-body and neck were made every 10 min to the nearest 0.5 units using the following standard visual analogue scales: thermal sensation (1=cold, 4=neutral, 7=hot (15)); thermal comfort (1=comfortable, 4=very uncomfortable (14)); and skin wettedness (+3=very wet, +2=wet, +1=slightly wet, 0=neutral, -1=slightly dry, -2=dry, -3=very dry (26)).

Familiarization Protocol

At least 24 hrs prior to experimental testing, participants reported to the laboratory to perform a peak oxygen uptake (VO_2peak) test and were familiarized with how to use the neck device, and with the perceptual questionnaires. The VO_2peak test was used to determine the relative cycling intensity that would elicit a moderate (~55% VO_2peak) relative exercise intensity. Participants completed a 5 min warm up on the cycle ergometer at a resistance of their choice, followed by two minutes of rest, after which 2 min of baseline measures were collected. The first stage of the VO_2peak protocol began immediately following baseline measures. Participants chose a cadence between 70-80 rpm. The actual cadence was maintained throughout the duration of the test and during the subsequent experimental trial.

The first stage began at 0.5 kp for females and 1.0 kp for males, and increased by 0.25 kp every minute thereafter until volitional exhaustion, defined as the inability to maintain their cadence within 10 rpm of the required cadence. VO_2peak was identified as the highest oxygen consumption value (per minute) measured during the test. Following the VO_2peak test, participants relaxed in a chair where the neck device was placed on them and they were permitted to open and close the valve as they wished. At this point in time, they were familiarized and asked to respond to each perceptual scale.

Experimental protocol

Participants arrived at the laboratory for their experimental trial euhydrated, confirmed via urine specific gravity <1.020 (actual urine specific gravity: 1.011 ± 0.007), and having refrained from strenuous exercise, alcohol and caffeine for 12 h, and food for 2 h. All experimental testing was conducted during the winter months in Buffalo, NY (outside temperature on experimental days: -2 ± 5°C). Participants wore a standard short sleeved crew t-shirt and running shorts (men or women's cut), and their own socks and athletic shoes (~0.4 clo).

The experimental trial took place in a moderate thermal environment (27.0 ± 1.0°C, 22 ± 4% relative humidity). Following instrumentation, participants sat on a mesh chair behind a standard upright cycle ergometer (Monark 828E, Sweden) for 10 min. Participants were then carefully transferred to the cycle ergometer for 30 min of moderate intensity cycling at 81± 22 W (55 ± 7% VO_2max, 281 ± 51 $W \cdot m^2$). This was followed by 120 min seated recovery on the aforementioned mesh chair. Participants were allowed to watch non-stimulating documentaries throughout the entire protocol.

Data and statistical analyses

Continually recorded data were binned as 60 s averages every 10 min. These data are reported as absolute values. The temporal data were analyzed for changes over time using one-way repeated measures ANOVAs. For the temporal data, when a significant F test was identified, a priori Sidak post hoc comparisons were made between pre-exercise (i.e., 10 min pre-exercise) and end-exercise (i.e., 30 min exercise) time points. To determine the relative contributions of mean skin wettedness, core temperature and mean skin temperature to thermal behavior, continually recorded data were binned as 60 s averages every minute throughout. Multiple linear regression analyses were performed from these data for each individual participant, inclusive of all pre-exercise, exercise and recovery timepoints. The independent variables were mean skin wettedness, core temperature and mean skin temperature and neck device temperature was the dependent variable. All independent variables were log transformed to reduce confounding issues associated with multicollinearity in the dataset that could affect the resulting beta coefficients (32). The absolute value of each standardized beta coefficient for mean skin temperature, core temperature and mean skin wettedness from each individual multiple linear regression model were used to calculate the relative contribution of each independent variable for each subject. For example, the relative percent contribution of a given independent variable (e.g., ‘a’) was calculated from the standardized beta coefficient for this variable (e.g., βa) as a function of the sum of all of the standardized beta coefficients (e.g., $\beta a \div (\beta a+\beta b+\beta c) \times 100$). This was completed for each variable and in each subject. The mean of all individual relative contributions were taken to provide an overall percent contribution of each variable to thermal behavior (i.e. neck device temperature). A similar analysis has been used previously to delineate the relative contributions of core and mean skin temperature on thermal comfort (11) and thermal behavior (35). Mean data for the individual standardized beta coefficients and the relative contributions were analyzed using a one-way repeated measures ANOVA. Pearson’s correlation analyses were also run on individual data collected every 10 min during rest, exercise and recovery between the following variables: mean skin wettedness and perceived whole body skin wettedness, mean skin wettedness and perceived thermal comfort. For these analyses, perceptual values were changed to percentages for comparison with mean body wettedness and thermal behavior. Spearman’s correlations for non-parametric data were run on perceived whole-body skin wettedness and perceived thermal comfort data. Mean R^2 values and P-values were pooled to determine the strength of the relationships. Mulitple linear regression analyses were carried out using SPSS (Version 22, IBM Analytics, Armonk, NY), while all other analyses were carried out using Prism (Version 7, GraphPad Software Inc., La Jolla, CA). For all analyses, *a priori* statistical significance was set at $P \leq 0.05$ and actual P-values are reported where possible.

Results

Body temperatures and mean skin wettedness

Mean skin temperature decreased from pre-exercise at 10 min during exercise ($P<0.01$) and was not different from pre-exercise during recovery at any time point ($P \geq 0.42$). Mean skin temperature also did not differ from the end of exercise at any time during recovery ($P \geq 0.72$) (Figure 1A). In contrast, core temperature was elevated over pre-exercise levels 10 min into exercise and remained elevated until 30 min post-exercise ($P \leq 0.04$). Core temperature decreased from end-exercise values within the first 10 min in the post-exercise period and continued to fall towards pre-exercise levels thereafter ($P<0.01$) (Figure 1B). Mean skin wettedness increased above pre-exercise levels 20 min into exercise and remained elevated until 80 min into recovery ($P \leq 0.05$). Mean skin wettedness peaked at the end of exercise and, compared to this point, was decreased at 20 min into recovery and thereafter ($P \leq 0.01$) (Figure 1C).

Thermoeffectors

Neck device temperature was lower than at pre-exercise 10 min into exercise and remained depressed until 20 min into recovery ($P \leq 0.03$). Following the cessation of exercise, neck device temperature began to climb back toward pre-exercise levels but was only different from end-exercise after 60 min into recovery ($P \leq 0.04$) (Figure 2A). Neck skin temperature was lower than at pre-exercise 20 min into exercise and remained lower until 30 min into recovery ($P \leq 0.03$). Compared to the end of exercise, neck skin temperature was only different between 80 and 110 min into recovery ($P \leq 0.02$) (Figure 2B). Average local sweat rate was elevated over pre-exercise levels at 10 min into exercise and peaked at the end of exercise ($P<0.01$), whereafter it decreased back towards pre-exercise levels within the first 10 min of recovery and remained thereafter ($P \geq 0.35$) (Figure 2C). Forearm skin blood flow increased and peaked at 30 min of exercise ($P<0.01$) and remained elevated until 20 min into recovery ($P \leq 0.04$) (Figure 2D).

Thermal perceptions

The neck was perceived to be thermally comfortable at baseline and did not change during exercise ($P>0.66$) or recovery ($P>0.99$) (Figure 3A). Participants also perceived their whole body to be thermally comfortable prior to exercise. However, whole-body thermal discomfort increased throughout all of exercise ($P \leq 0.04$), and returned to pre-exercise levels with the first 10 min of recovery, where it remained thereafter ($P \geq 0.93$) (Figure 3B). Thermal sensations of the neck were perceived to be neutral at baseline and throughout exercise ($P>0.99$) and recovery ($P>0.99$) (Figure 3C). Whole body thermal sensation was perceived to be neutral before exercise, and warmth sensations became evident at 20 min of exercise ($P<0.01$), peaking at end-exercise ($P=0.03$). Perceptions of whole body thermal sensation returned to pre-exercise levels at 10 min and remained throughout recovery ($P \geq 0.80$) (Figure 3D). During pre-exercise, neck skin wettedness was perceived to be slightly dry, but became slightly wet 20 min into exercise and remained throughout the first 10 min ito recovery ($P \leq 0.03$), but returned to baseline afterwards ($P \geq 0.63$) (Figure 3E). Similar to perceptions of neck skin wettedness, perceptions of whole body skin wettedness were perceived to be slightly dry prior to exercise and increased between slighty wet and wet by the end of exercise ($P \leq 0.03$). Perceptions of whole body skin wettedness decreased within 20 min and remained throughout recovery ($P \geq 0.44$). Compared to the end of exercise, perceptions of whole body wettedness decreased within the first 10 min of recovery and remained throughout ($P<0.01$) (Figure 3F).

Relative contributions to thermal behavior

Core temperature data from 2 participants were only collected every 10 min. Therefore, these data were excluded from the relative contributions analysis (n=14). The mean of all models for combined individual data was significant (R^2 = 0.636 ± 0.194 , P<0.01 ± 0.00). The standardized beta coefficient for mean skin wettedness (0.673 ± 0.349) was greater than both core (0.269 ± 0.271, P=0.04) and mean skin temperature (0.354 ± 0.257, P=0.03), but did not differ between mean skin temperature and core temperatures (P=0.72) (Table 2). Mean skin wettedness (52 ± 24%) contributed to thermal behavior to a greater extent than mean skin temperature (26 ± 16%, P=0.04), but not core temperature (22 ± 22%, P=0.06). The core and mean skin temperature contributions to thermal behavior did not differ (P=0.93) (Figure 4).

Correlations of skin wettedness, thermal behavior and perceptions

One individual did not perceive thermal comfort to change during the protocol and was therefore not included in the analysis (n=15). A moderate, positive correlation was found between the total percentage of whole body skin wettedness and perceptions of whole body skin wettedness (R^2=0.441 ± 0.240; P=0.057 ± 0.105). Likewise, perceptions of whole body skin wettedness and whole body thermal comfort were found to be moderately correlated (R^2=0.461 ± 0.249 P=0.069 ± 0.134). However, only a weak relationship was found between the the total percentage of whole body skin wettedness and perceptions of whole body thermal comfort (R^2=0.284 ± 0.166; P=0.12 ± 0.21).

Discussion

The present study aimed to determine the extent to which mean skin wettedness contributes to thermal behavior during exercise and after exercise, compared to core and mean skin temperatures. In support of our hypothesis, we have identified that mean skin wettedness contributes to thermal behavior to a greater extent compared to mean skin and core temperatures. These findings highlight the importance of measuring skin wettedness when examining mechanisms and contributing factors to thermal behavior, particularly during situations that elicit sweat production and accumulation (e.g., exercise, passive heat stress).

Importance of skin wettedness to thermal behavior during exercise and recovery

In the present study, participants cycled at a moderate exercise intensity that was sufficient to elevate core temperature and stimulate sudomotor activity. Participants were required to maintain the thermal comfort of their neck (i.e., a 1.0 on the thermal comfort scale), and were reminded to thermally behave by turning a neck cooling device on or off as necessary. Using this model, we have previously shown that core temperature contributed to thermal behavior to a greater extent than mean skin temperature during and following 60 min of low intensity exercise (35). This approach, however, omitted the potential contribution of skin wettedness to thermal behavior. In fact, skin wettedness has generally been overlooked as a contributor to thermal behavior despite its known contributions to thermal discomfort (12). This is likely due to our relatively little understanding of how skin wettedness afferent information is transmitted. Specifically, unlike thermoreceptors that send information directly back to the central nervous system to be integrated and bring about thermoeffector activation, humans do not posses hygroreceptors that provide wettedness afferent feedback (6). Rather, humans learn to perceive skin wettedness based on the integration of thermo- and mechano-receptor information (8). Nevertheless, it has been suggested that skin wettedness (and the perception thereof), occurring secondary to the buildup of sweat on the skin, plays a key role in thermal behavior alongside thermal afferent feedback during exercise, particularly in the heat (10). To our knowledge, this is the first study to directly examine the relationships between mean skin wettedness, core temperature, mean skin temperature, and thermal behavior. As such, the present data reveal that ~52% of the contribution to thermal behavior, or the desire to receive cooling on the neck, was stimulated by mean skin wettedness, with only ~26% and ~22% coming from mean skin and core temperatures, respectively. It is notable that, although the comparison of relative contributions between mean skin wettedness and core temperature only approached statistical significance (P=0.06), the standardized beta coefficients were different between these variables (P=0.04). Collectively, therefore, we interpret these findings that mean skin wettedness contributes to thermal behavior to a greater extent than both core and mean skin temperatures.

It is thought that increases in skin wettedness during exercise cause thermal discomfort in spite of reductions in skin temperature occurring secondary to sweat evaporation (16). A threshold skin wettedness value of ~0.36 a.u. appears to elicit thermal discomfort during exercise at a rate of metabolic heat production of ~175 $W{\cdot}m^2$ (12). In support of this, metabolic heat production in the present study was 281 ± 51 $W{\cdot}m^2$ and mean skin wettedness peaked at 0.48 ± 0.08 a.u. (i.e., sweat covering ~48% of the body surface) by the end of exercise. With these increases in metabolic heat production and whole body skin wettedness, our observations of perceptions of 'slightly uncomfortable' for whole body thermal discomfort during exercise are in line with other investigations (13, 17).

During recovery from exercise, thermal behavior is thought to promote the restoration of core temperature and improve thermal comfort, which occurs at a time when autonomic heat loss thermoeffectors are effectively 'switched off' (35). To our knowledge, the data presented in the current study are the first to show that mean skin wettedness remains elevated well into the recovery period (Figure 1). The difference between the temporal dynamics of average local sweat rate and mean skin wettedness are perhaps most striking. Post-exercise, at a time when core temperature remains elevated and sudomotor activity is withdrawn, the skin remains wet for some time thereafter. This suggests that there may remain a medium to promote sweat evaporation, despite that sweat rate has returned to pre-exercise levels. That said, some of this wettedness is likely the result of sweat buildup in the microclimate, which ultimately may not provide the same rate of evaporative cooling as bare skin.

Nevertheless, mean skin wettedness appears to be important for the continued activation of thermal behavior post-exercise, although the independent factor of bare vs. clothed skin warrants further investigation. In summary, this is the first study to quantify the relative importance of mean skin wettedness to thermal behavior during exercise and recovery. Our findings suggest that even at moderate exercise intensities and in a moderate thermal environment, whole body skin wettedness is an important factor in contributing to thermal behavior alongside changes in core temperature and mean skin temperature.

The importance of skin wettedness on perceptions of skin wettedness and thermal comfort

Humans perceive skin wettedness through mechanoreceptor activation and reductions in skin temperature (8, 9). Previous analyses have demonstrated strong positive correlations between increases in whole body skin wettedness and thermal discomfort (12, 17). Further to this, it has been shown that the pressure of clothing (i.e., tight versus loose fitting) can influence wetness perception (8). However, specific fabric textiles (i.e., rough versus smooth) used in clothing do not significantly contribute to wetness perception during dynamic activities, although they can increase sensations of pleasantness and therefore, thermal comfort (27). Interestingly, our analyses did not reveal that skin wettedness and thermal discomfort were strongly correlated in the present study (R^2=0.284 ± 0.166, P=0.12 ± 0.22). One reason for this may be because we modeled our data individually in order to determine mean correlations. Furthermore, we employed a relatively short exercise duration and only had modest increases in thermal discomfort, despite similar levels of mean skin wettedness to the aforementioned studies during exercise. Still, we were able to demonstrate a moderate positive correlation between whole body skin wettedness and whole body wettedness perceptions (R^2=0.441 ± 0.240, P=0.057 ± 0.105), and between whole body wettedness perception and perceptions of thermal discomfort (R^2=0.461 ± 0.249, P=0.069 ± 0.134). Collectively, these findings raise the question regarding whether the perception of skin wettedness or actual skin wettedness is the more important mediator of thermal discomfort and/or thermal behavior. In fact, it may be that actual skin wettedness is less important than the perceived magnitude of skin wettedness. For instance, considering that thermal behavior during exercise is driven by increases in thermal discomfort (30), it is likely that the perceived thermal discomfort is contributed to by perceptions of warmth and skin wettedness. Skin wettedness perception is brought about by acute reductions in skin temperature and/or mechanoreceptor stimulation, which normally occurs secondary to actual skin wettedness caused by sweat evaporation and buildup on the skin, respectively. Thus, any situation that results in reductions in skin temperature and/or mechanoreceptor stimulation could theoretically stimulate thermal behavior independent of actual skin wettedness. This remains to be elucidated. Clearly, therefore, the specific mechanisms and interactions between actual skin wettedness, perceived skin wettedness and thermal behavior deserve further investigation.

Considerations

In this study, mean skin wettedness was calculated as the mean of 8 sites collected using iButtons raised about 6mm off the skin. While we are confident that this represents actual wettedness, it is important to note that 5 of these sites were under clothing. Collecting data under clothing represents a real-life situation, and hence we deemed this appropriate. For instance, it is not uncommon for individuals to remain in their clothing after exercising, especially at moderate exercise intensities. However, there is a possibility that outside of the laboratory, individuals would change out of their clothing secondary to sweat buildup and/or sweat perception, which in itself may be evidence of the important contribution that mean skin wettedness imparts on thermal behavior. Additionally, it is important to draw attention to the fact that the findings presented herein are constrained to the conditions employed (i.e., moderate exercise intensity on a cycle ergometer, in a moderate thermal environment by young, healthy and active participants). Therefore, it is unknown if these weightings hold true during passive heat stress or exercise in the heat. Further research is warranted using different exercise intensities, environments, or other situations in which heat stress results in changes in body temperatures and subsequent activation of sweating. A potential limitation of the present study is our use of a telemetry pill to measure core temperature. This is particularly important considering the relatively slower responsiveness to changes in body heat content of the telemetry pill compared to esophageal temperature (23). It is possible, therefore, that our measure of core temperature was underestimated during transitions from rest to exercise and overestimated during transitions from exercise to recovery. That said, because participants ingested the pill 60 min prior to the study, the limited transit time into the GI tract is believed to have better responsiveness time than rectal temperature (3) and supports our use of the pill therefore. Additionally, we only had female participants self-report menstrual cycle phase, and therefore do not know their hormone levels at the time of testing. It should also be noted that these findings are not causal. Rather, we have demonstrated that mean skin wettedness explains a greater proportion of the variability in thermal behavior when compared to mean skin and core temperatures. This was demonstrated using multiple linear regression analysis on time-series data sampled at a relatively high frequency. It is worth mentioning that using time-series data may have inflated the significance values reported herein. That said, the use of time-series data was deemed appropriate because collecting one data point per subject per time point was not feasible and because we modeled our data on a per subject basis (i.e., not pooled). Moreover, to reduce the potential confounding influence of multicollinearity on the beta coefficients arising from the linear regression models, we used data obtained throughout exercise and recovery, as opposed to analyzing the exercise and recovery time periods separately (32). This prevents conclusions regarding whether the contributions of skin wettedness, core temperature, and mean skin temperature differ between rest and recovery. Notably, however, such differences appear unlikely (35). It is clear, therefore, that despite the utility of using multiple linear regression in the present study, this approach is not without limitations. Thus, further studies are required to experimentally examine the contributions of skin wettedness, skin temperature, and core temperature by independently manipulating these variables and measuring the thermal behavioral outcome. Finally, the variability in the beta coefficient of determinination in linear regression analysis highlights the percentage that factors outside our present variables may contribute to thermal behavior. Our models revealed significant R^2 values for the model ($R^2 = 0.636 \pm 0.194$, $P<0.01 \pm 0.00$). These values suggest that the combination of mean skin and core temperatures and mean skin wettedness contribute ~64% to thermal behavior during exercise and recovery. Hence, while these variables appear to account for a large quantity of the variation, there are likely other thermal or non-thermal factors that may also contribute to thermal behavior. This deserves further investigation.

Perspectives

To this point, the afferent stimulus for thermal behavior has been quantified only using mean body temperature, a weighted average of core and mean skin temperatures (35). Considering the findings from the present study, however, it is advisable that when examining the control of thermal behavior when body temperature increases and sweat production is expected, the thermal afferent stimulus should include a measure of mean skin wettedness. Although tightly constrained to the present exercise intensity, modality and environmental conditions, this study is the first to identify a new combination of thermal and skin wettedness stimuli that is likely to be more representative of the integrated afferent stimuli that contributes to thermal behavior. In conditions similar to those employed in the present study, it would be advisable that the mean afferent stimuli be used, rather than only the mean body temperature. This mean afferent stimulus should include mean skin temperature, core temperature, and mean skin wettedness weighted in the following manner: mean skin temperature: 0.26, core temperature: 0.22 and mean skin wettedness: 0.52. These weightings represent the average of the relative contribution to exercise and recovery as we were unable to tease out exercise compared to recovery to reduce the error associated with multicollinearity within our data sets. Despite this evidence, there remains a considerable amount of work to be done regarding the extent to which skin wettedness is a driver of thermal behavior. For instance, it is important to identify how these relative weightings may differ in alternate modes and intensities of exercise, environmental conditions and with different types or levels of clothing coverage. The findings from the present study also highlight the need to further understand mechanisms underlying relationships between physiological changes (i.e., change in actual mean skin wettedness and actual mean body temperatures) and the perceptions that drive thermal discomfort and thermal behavior. A more thorough understanding of these mechanisms will provide the necessary tools to study how changes in these variables alter thermal behavioral responses and the motivation to behave in both healthy and 'at risk' populations (e.g., Multiple Sclerosis, cardiovascular disease, older adults, etc.).

Conclusions

This study demonstrates that mean skin wettedness likely contributes to thermal behavior to a greater extent than both mean skin temperature and core temperature during and after exercise that results in sweat production and accumulation on the skin and within the microclimate. Furthermore, this study provides further evidence that skin wettedness is associated with perceptions of skin wettedness and thermal discomfort. Considering the present findings, it is suggested that future research aiming to study the mechanisms and contributing factors to thermal behavior in humans should incorporate measures of skin wettedness, in addition to mean skin temperature and core temperature, particularly in instances when sweat production is expected.

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analysis and drafting of the manuscript. All authors approved the final manuscript. Zachary Schlader has received travel reimbursement from lululemon athletica inc. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Table 1 Subject characteristics, mean ± SD. [b]All participants were in the normal range for their age ground (≥25 points) (28).

Table 2 Standardized beta coefficients (absolute values) from individual linear regressions for relative contributions of mean skin wettedness, core temperature and mean skin temperature to neck device temperature (n=14). Mean skin wettedness, core temperature and mean skin temperature are independent variables and neck device temperature is the dependent variable. *Different from core (P=0.04) and mean skin temperatures (P=0.04).

Figure 1 Mean skin temperature (A), core temperature (B), and mean skin wettedness (C) during exercise and recovery (n=16, mean ± SD). [P] Different from pre-exercise (P≤0.05). [E]Different from end-exercise (P<0.01).

Figure 2 Neck device temperature (A), neck skin temperature (B), average local sweat rate (C) and forearm skin blood flow (D) during exercise and recovery (n=16, mean ± SD). [P] Different from pre-exercise (P≤0.04). [E]Different from end-exercise (P≤0.04).

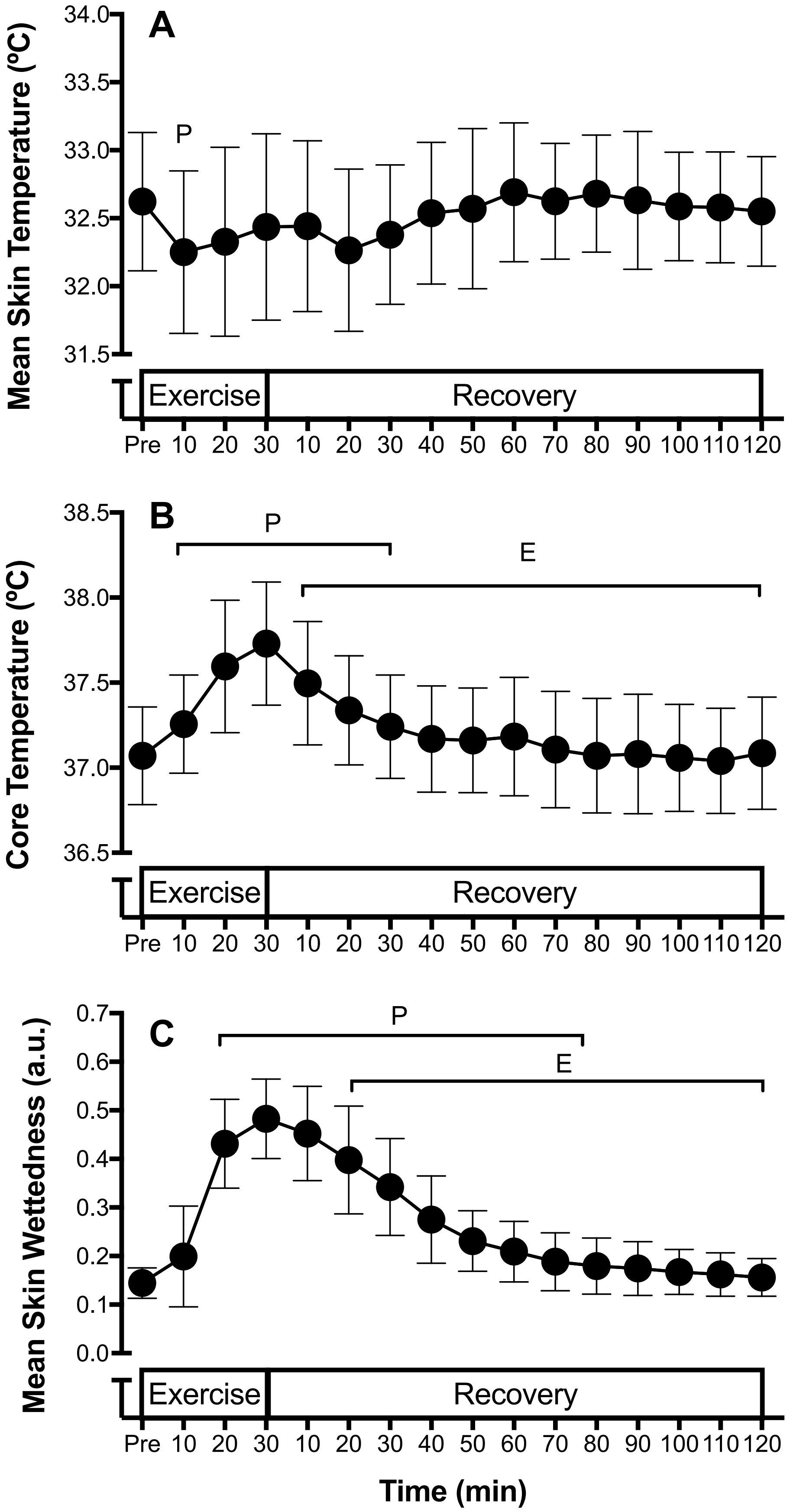
Figure 3 Neck thermal comfort (A), whole body thermal comfort (B), neck thermal sensation (C), whole body thermal sensation (D), neck skin wettedness (E) and whole body skin wettedness (F) during exercise and recovery (n=16, mean ± SD). [P]Different from pre-exercise (P≤0.03). [E]Different from end-exercise (P≤0.02).

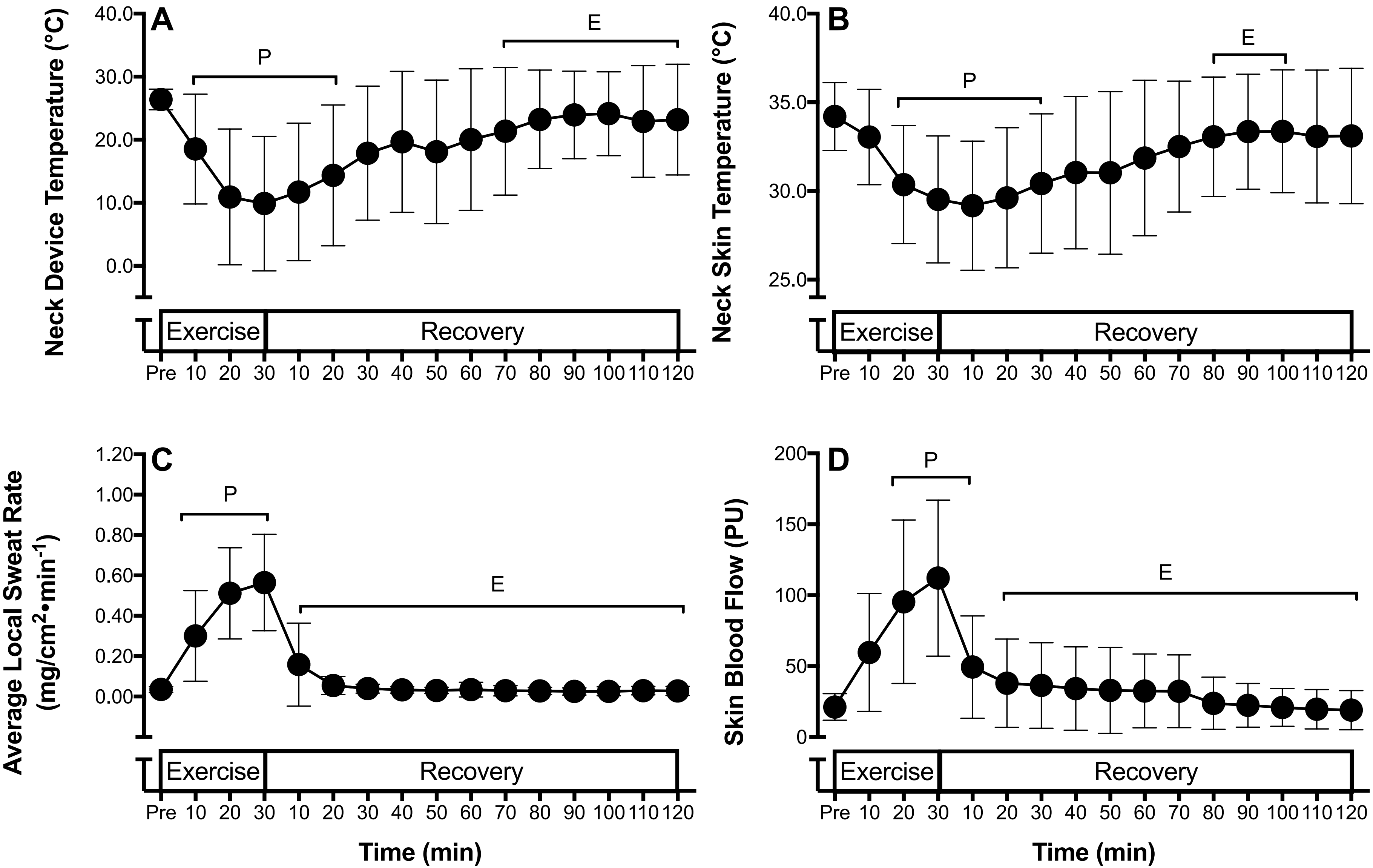
Figure 4 Relative contributions of mean skin wettedness, core temperature and mean skin temperature (n=14, mean ± SD) to neck device temperature throughout the protocol. *Greater than mean skin temperature (P=0.04).

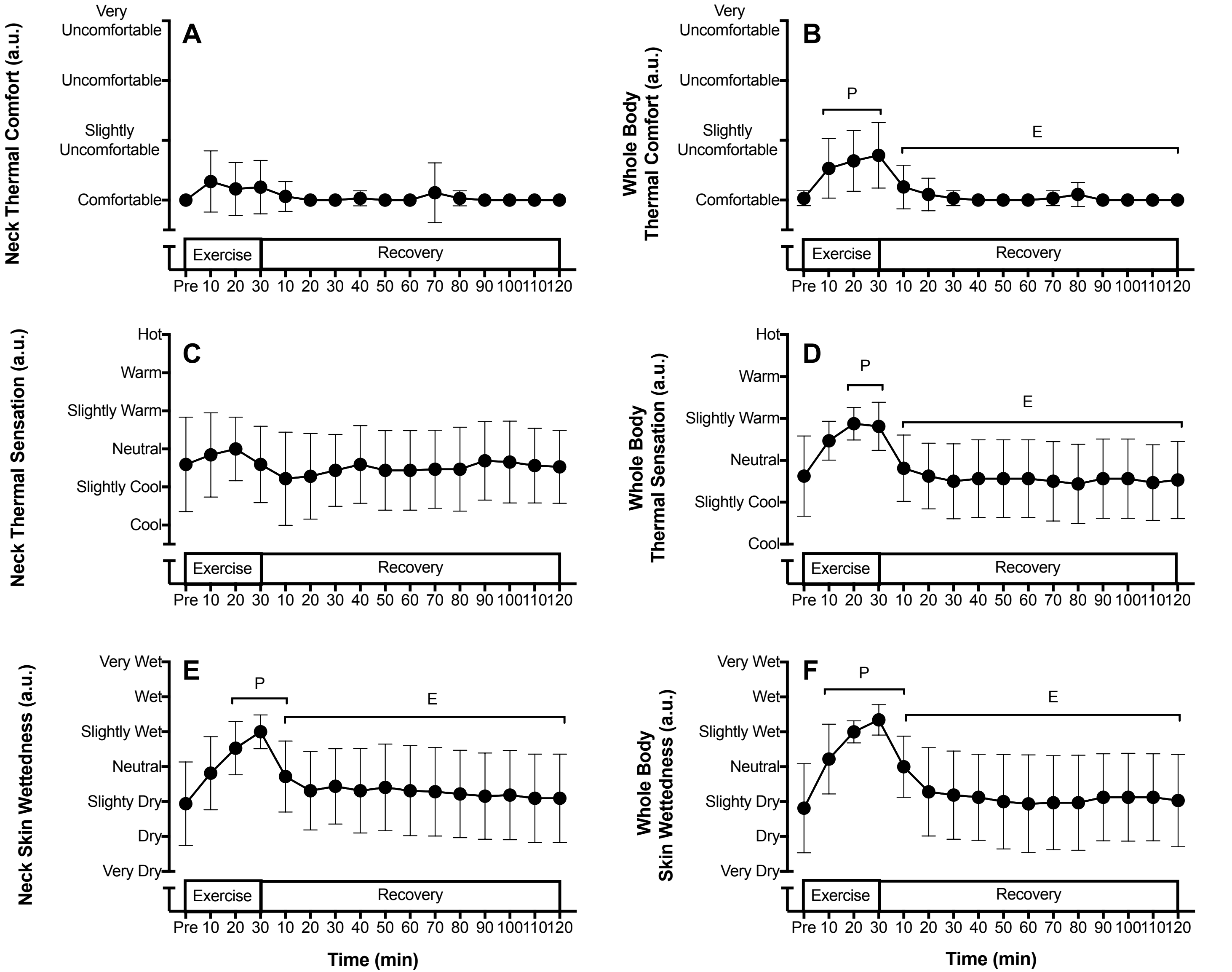
Table 1. Subject Characteristics (mean ± SD).

Number of subjects	16 (8 females)
Age (y)	23 ± 3
Height (cm)	169 ± 7
Weight (kg)	72 ± 13
Body surface area (m^2)	1.82 ± 0.20
Body fat (%)	15.5 ± 6.8
VO_2peak (ml/kg/min)	41.8 ± 7.0
Montreal Cognitive Assessment Score	29 ± 1[a]

[a]all subjects were in the normal range (≥ 25) for age group (40).


A
Mean Skin Temperature (ºC)
34.0
33.5
33.0
32.5
32.0
31.5
P
Exercise
Recovery
Pre
10
20
30
10
20
30
40
50
60
70
80
90
100
110
120
B
Core Temperature (ºC)
38.5
38.0
37.5
37.0
36.5
P
E
Exercise
Recovery
C
Mean Skin Wettedness (a.u.)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
P
E
Exercise
Recovery
Time (min)


A
Neck Device Temperature (°C)
40.0
30.0
20.0
10.0
0.0
P
E
Exercise
Recovery
Pre 10 20 30 10 20 30 40 50 60 70 80 90 100 110 120
B
Neck Skin Temperature (°C)
40.0
35.0
30.0
25.0
P
E
Exercise
Recovery
Pre 10 20 30 10 20 30 40 50 60 70 80 90 100 110 120
C
Average Local Sweat Rate
(mg/cm²•min⁻¹)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
P
E
Exercise
Recovery
Pre 10 20 30 10 20 30 40 50 60 70 80 90 100 110 120
Time (min)
D
Skin Blood Flow (PU)
200
150
100
50
0
P
E
Exercise
Recovery
Pre 10 20 30 10 20 30 40 50 60 70 80 90 100 110 120
Time (min)



A
Neck Thermal Comfort (a.u.)
Very Uncomfortable
Uncomfortable
Slightly Uncomfortable
Comfortable
Exercise
Recovery
Pre 10 20 30 10 20 30 40 50 60 70 80 90 100 110 120
B
Whole Body Thermal Comfort (a.u.)
P
E
C
Neck Thermal Sensation (a.u.)
Hot
Warm
Slightly Warm
Neutral
Slightly Cool
Cool
D
Whole Body Thermal Sensation (a.u.)
E
Neck Skin Wettedness (a.u.)
Very Wet
Wet
Slightly Wet
Neutral
Slighty Dry
Dry
Very Dry
F
Whole Body Skin Wettedness (a.u.)
Time (min)

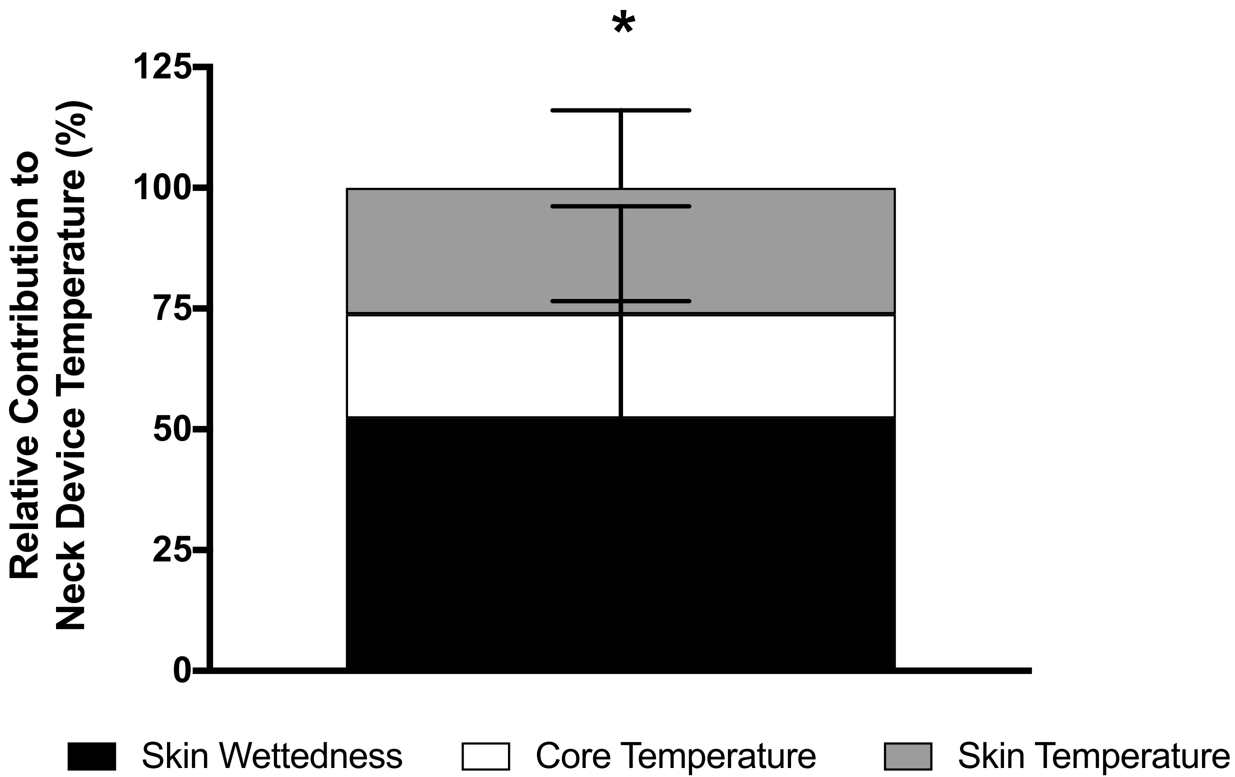

*
Relative Contribution to
Neck Device Temperature (%)
125
100
75
50
25
0
Skin Wettedness
Core Temperature
Skin Temperature

Table 2. Individual standardized beta coefficients (absolute values) for mean skin wettedness, core and mean skin temperatures to thermal behavior throughout the protocol (n=14)

Subject	Mean Skin Wettedness	Core Temperature	Mean Skin Temperature	R^2	P-value
1	0.444	0.109	0.451	0.741	<0.01
2	0.702	0.039	0.249	0.370	<0.01
3	0.269	0.196	0.323	0.570	<0.01
4	1.029	0.177	0.327	0.774	<0.01
5	1.001	0.135	0.018	0.783	<0.01
6	0.464	0.839	0.846	0.519	<0.01
7	0.176	0.333	0.487	0.355	<0.01
8	0.164	0.777	0.035	0.834	<0.01
9	0.999	0.481	0.654	0.529	<0.01
10	0.724	0.010	0.394	0.345	<0.01
11	0.939	0.003	0.076	0.955	<0.01
12	1.058	0.061	0.697	0.818	<0.01
13	0.371	0.419	0.076	0.634	<0.01
14	1.076	0.183	0.325	0.675	<0.01
Mean ± SD	0.673±0.349*	0.269 ±0.271	0.354±0.257	0.636±0.194	<0.01 ± 0.00

Standardized beta coefficients (absolute values) are from multiple linear regression with mean skin wettedness, core temperature and mean skin temperature as independent variables and neck device temperature as the dependent variable. *Greater than mean skin (P=0.04) and core temperatures (P=0.04).